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Chiral Dynamics and Dubna-Mainz-Taipei Dynamical Model for Pion-Photoproduction Reaction

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We demonstrate that the Dubna-Mainz-Taipei (DMT) meson-exchange dynamical model, which starts from an effective chiral Lagrangian, for pion photoproduction provides an excellent and economic framework to describe both the π^0 threshold production and the Δ deformation, two features dictated by chiral dynamics.

Keywords: Chiral symmetry; threshold π^0 production; baryon deformation.

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An important feature of the low-energy QCD is the chiral symmetry. Chiral symmetry is expected to show up in the parity doubling of all hadronic states (Winer-Weyl mode), e.g., the proton with $J^P = 1/2^+$ would have a $1/2^-$ partner. This is not observed experimentally. Instead the symmetry is broken spontaneously (Nambu-Goldstone mode) which leads to the appearance of massless pseudoscalar mesons. The opposite parity partner of the proton is a proton plus a "massless pion".

Spontaneous chiral symmetry breaking (SCSB) has led to the development of chiral perturbation theory (ChPT), a low-energy effective field theory of QCD. It utilizes the concept of SCSB and replaces the quark and gluon fields by a set of fields describing the degrees of freedom of the observed hadrons. There is generally good agreement between the ChPT predictions and experiments¹, including the π^0 photoproduction near threshold where very precise measurements have been performed and the ChPT calculation to one loop $O(p^4)$ has been carried out in the heavy-baryon formulation².

The fact that opposite parity partner of the proton is a proton plus a pion leads to the consequence that the πN interaction in momentum space takes the form $V_{\pi N} = g_{\pi N} \vec{\sigma} \cdot \vec{q}$, where $\vec{\sigma}$ and \vec{q} are the nucleon spin and pion momentum, respectively. This strong p -wave πN interaction gives rise to the Δ resonance and its deformation³, which has been observed in pion photoproduction.

In this contribution, I will present a meson-exchange dynamical model for pion photoproduction we recently developed in a collaboration between groups at Dubna, Mainz, and Taipei (DMT)⁴ which can describe well the pion-photoproduction data from threshold to the first resonance region, including the π^0 threshold production

2 Authors' Names

and Δ deformation. The DMT dynamical model also starts from an effective chiral Lagrangian. The effective Lagrangian is then used to construct a potential for use in the scattering equation. The solutions of the scattering equation will include rescattering effects to all orders and thereby unitarity is ensured.

In a dynamical model for pion photoproduction⁵, the t -matrix is given as $t_{\gamma\pi}(E) = v_{\gamma\pi} + v_{\gamma\pi}g_0(E)t_{\pi N}(E)$, where $v_{\gamma\pi}$ is the $\gamma\pi$ transition potential, g_0 and $t_{\pi N}$ are the πN free propagator and t matrix, respectively, and E is the total energy in the c.m. frame. Physical multipole amplitude in channel α then reads as⁵

$$t_{\gamma\pi}^{(\alpha)}(q_E, k_E; E + i\varepsilon) = e^{i\delta_\alpha} \cos \delta_\alpha [v_{\gamma\pi}^{(\alpha)} + P \int_0^\infty dq' \frac{q'^2 R_{\pi N}^{(\alpha)}(q_E, q'; E) v_{\gamma\pi}^{(\alpha)}(q', k_E)}{E - E_{\pi N}(q')}]_{(1)}$$

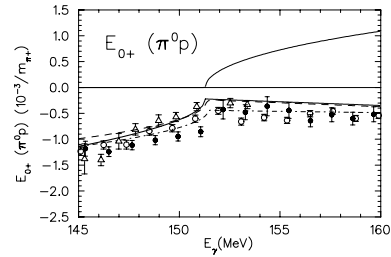
where δ_α , $R_{\pi N}^{(\alpha)}$, $E_{\pi N}(q)$ and P denote the πN phase shift, reaction matrix in channel α , total CM energy of momentum q , and principal value integral, respectively; $k_E = |\mathbf{k}|$ is the photon momentum and q_E the pion on-shell momentum. The amplitudes $t_{\pi N}$ are obtained in a meson-exchange πN model⁶ constructed in the Bethe-Salpeter formalism and solved within Cooper-Jennings reduction scheme. At low energies where resonances play little role, only background part, $v_{\pi N}^B$ and $v_{\gamma\pi}^B$, which are derived from an effective Lagrangian containing Born terms and ρ and ω exchanges in the t channel, contribute.

For π^0 photoproduction from proton, we calculate the multipole E_{0+} near threshold by solving the following coupled channels equation within a basis with physical pion and nucleon masses. It leads to the following expression in $\pi^0 p$ channel:

$$t_{\gamma\pi^0}(E) = v_{\gamma\pi^0}(E) + v_{\gamma\pi^0}(E) g_{\pi^0 p}(E) t_{\pi^0 p \rightarrow \pi^0 p}(E) \\ + v_{\gamma\pi^+}(E) g_{\pi^+ n}(E) t_{\pi^+ n \rightarrow \pi^0 p}(E). \quad (2)$$

The πN t -matrices are obtained by solving the coupled channels equation for πN scattering using the meson-exchange model⁶. In Fig. 1, the prediction of DMT model for $Re E_{0+}$ obtained without and with isospin symmetry assumption, are shown in dashed and solid curves, respectively, and compared with heavy-baryon ChPT results (dash-dotted curve)². Agreement of DMT prediction with the data

Fig. 1. Real part of the E_{0+} multipole for $\gamma p \rightarrow \pi^0 p$. The dashed and solid curves are the full DMT results obtained without and with isospin symmetry assumption, respectively. The dash-dotted curve is the result of ChPT. Data points are from various experiments⁷.



and ChPT results are excellent.

The polarized linear photon asymmetry Σ has been found to be very sensitive to small p -wave multipoles⁷. DMT model (solid curve) is not able to reproduce the data at 159.5 MeV, of Ref. 8, as shown in Fig. 2, while ChPT calculation of $O(p^4)$ with six low-energy constants (dashed curve) is seen to be able to describe the experiment reasonably well. However, preliminary analysis of a new measurement at Mainz⁹ seems to agree with DMT's prediction.

We now turn to the issue of the $\Delta(1232)$ deformation. In a symmetric SU(6) quark model, Δ is in S state and spherical. The photo-excitation of the Δ could then proceed only via $M1$ transition. The existence of a D state in the Δ has the consequence that the Δ is deformed and the photon can excite a nucleon through electric $E2$ quadrupole transition. In pion photoproduction, $E2$ excitation would give rise to nonvanishing $E_{1+}^{(3/2)}$ multipole amplitude. Recent experiments give $R_{EM} = E_{1+}^{(3/2)}/M_{1+}^{(3/2)} = -(2.5 \pm 0.5)\%$ ¹⁰, a clear indication of Δ deformation.

In the $(3,3)$ channel where Δ excitation plays an important role, the transition potential $v_{\gamma\pi}$ consists of two terms

$$v_{\gamma\pi}(E) = v_{\gamma\pi}^B + v_{\gamma\pi}^\Delta(E), \quad (3)$$

where second term of Eq. (3) corresponds to the contribution of bare Δ , namely, $\gamma N \rightarrow \Delta \rightarrow \pi N$. We may then write

$$t_{\gamma\pi} = t_{\gamma\pi}^B + t_{\gamma\pi}^\Delta, \quad (4)$$

where $t_{\gamma\pi}^B(E) = v_{\gamma\pi}^B + v_{\gamma\pi}^B g_0(E) t_{\pi N}(E)$ and $t_{\gamma\pi}^\Delta(E) = v_{\gamma\pi}^\Delta + v_{\gamma\pi}^\Delta g_0(E) t_{\pi N}(E)$.

By combining the contributions of $t_{\gamma\pi}^B$ and $t_{\gamma\pi}^\Delta$ and using the bare $\gamma N \Delta$ coupling constants G_{M1} and G_{E2} for $M1$ and $E2$ transitions as free parameters, results of

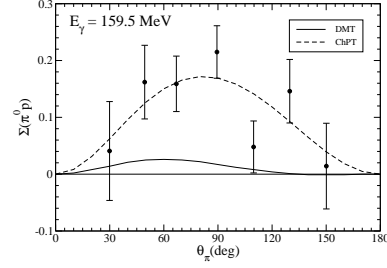


Fig. 2. Photon asymmetry at 159.5 MeV. The solid and dashed curves are results of DMT and ChPT calculations. Data are from Mainz⁸.

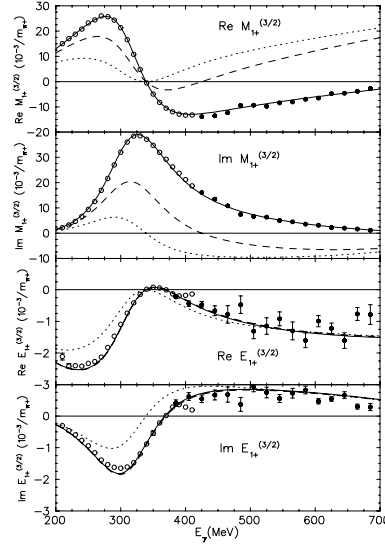


Fig. 3. Real and imaginary parts of the $M_{1+}^{(3/2)}$ and $E_{1+}^{(3/2)}$ multipoles. Dotted and dashed curves are the results for the $t_{\gamma\pi}^B$ obtained without and with principal value integral contribution in Eq. (1), respectively. Solid curves are the full results with bare Δ excitation. For the E_{1+} dashed and solid curves are practically the same due to a very small value of the bare G_{E2} . The open and full circles are the results from the analyses of Mainz¹¹ and VPI¹².

4 Authors' Names

our best fit to the resonant multipoles $M_{1+}^{(3/2)}$ and $E_{1+}^{(3/2)}$ obtained in the analyses of Mainz¹¹ and VPI group¹² are shown in Fig. 3 by solid curves. The dashed curves denote the contribution from $t_{\gamma\pi}^B$ only. The dotted curves represented the K -matrix approximation to $t_{\gamma\pi}^B$, namely, without the principal value integral term of Eq. (1) included.

For $M_{1+}^{(3/2)}$, one sees a large effect of the pion off-shell rescattering (difference between dotted and dashed curves), which results from the principal value integral part of Eq. (1). The total pion rescattering (dashed curves) contributes for half of the $M_{1+}^{(3/2)}$ as seen in Fig. 3 while the remaining half originates from the bare $\gamma N\Delta$ excitation. Furthermore, one sees that almost all of the $E2$ strength is generated by the πN rescattering.

At the resonance position $t_{\gamma\pi}^B$ vanishes within K -matrix approximation and only principal value integral term survives. The latter corresponds to the contribution where Δ is excited by the pion produced via $v_{\gamma\pi}^B$. Consequently the addition of this contribution to $t_{\gamma\pi}^\Delta$ can be considered as a dressing of the $\gamma N\Delta$ vertex. For $E_{1+}^{(3/2)}$, the dominance of background and pion rescattering contributions leads to a very small bare value for electric transition. We hence conclude that bare Δ is almost spherical and the deformation observed experimentally arises mostly from the long-range effect of the pion cloud, a manifestation of chiral dynamics.

In summary, we have demonstrated that the DMT meson-exchange dynamical model for pion photoproduction, which starts from an chiral effective Lagrangian, provides an excellent and economical framework in describing threshold π^0 production and Δ deformation, two key consequences of chiral dynamics.

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